

Results from CrIS/ATMS Obtained Using the AIRS Science Team Retrieval Methodology

Joel Susskind¹, Louis Kouvaris², and Lena Iredell²

¹NASA Goddard Space Flight Center, Greenbelt, MD, USA 20771

²SAIC, NASA Goddard Space Flight Center, Greenbelt, MD, USA 20771

ABSTRACT

AIRS was launched on EOS Aqua in May 2002, together with AMSU-A and HSB (which subsequently failed early in the mission), to form a next generation polar orbiting infrared and microwave atmospheric sounding system. AIRS/AMSU had two primary objectives. The first objective was to provide real-time data products available for use by the operational Numerical Weather Prediction Centers in a data assimilation mode to improve the skill of their subsequent forecasts. The second objective was to provide accurate unbiased sounding products with good spatial coverage that are used to generate stable multi-year climate data sets to study the earth's interannual variability, climate processes, and possibly long-term trends. AIRS/AMSU data for all time periods are now being processed using the state of the art AIRS Science Team Version-6 retrieval methodology. The Suomi-NPP mission was launched in October 2011 as part of a sequence of Low Earth Orbiting satellite missions under the "Joint Polar Satellite System" (JPSS). NPP carries CrIS and ATMS, which are advanced infra-red and microwave atmospheric sounders that were designed as follow-ons to the AIRS and AMSU instruments. The main objective of this work is to assess whether CrIS/ATMS will be an adequate replacement for AIRS/AMSU from the perspective of the generation of accurate and consistent long term climate data records, or if improved instruments should be developed for future flight. It is critical for CrIS/ATMS to be processed using an algorithm similar to, or at least comparable to, AIRS Version-6 before such an assessment can be made. We have been conducting research to optimize products derived from CrIS/ATMS observations using a scientific approach analogous to the AIRS Version-6 retrieval algorithm. Our latest research uses Version-5.70 of the CrIS/ATMS retrieval algorithm, which is otherwise analogous to AIRS Version-6, but does not yet contain the benefit of use of a Neural-Net first guess start-up system which significantly improved results of AIRS Version-6. Version-5.70 CrIS/ATMS temperature profile and surface skin temperature retrievals are of very good quality, and are better than AIRS Version-5 retrievals, but are still significantly poorer than those of AIRS Version-6. CrIS/ATMS retrievals should improve when a Neural-Net start-up system is ready for use. We also examined CrIS/ATMS retrievals generated by NOAA using their NUCAPS retrieval algorithm, which is based on earlier versions of the AIRS Science Team retrieval algorithms. We show that the NUCAPS algorithm as currently configured is not well suited for climate monitoring purposes.

Keywords: AIRS, CrIS, high spectral resolution IR sounders, retrieval methodology, IR sounding in cloudy conditions, Quality Control.

1. INTRODUCTION

AIRS was launched on EOS Aqua in May 2002, together with AMSU-A and HSB (which subsequently failed early in the mission), to form a next generation polar orbiting infrared and microwave atmospheric sounding system¹. AIRS/AMSU had two primary objectives. The first objective was to provide real-time data products available for use by the operational Numerical Weather Prediction Centers in a data assimilation mode to improve the skill of their subsequent forecasts. The second objective was to provide accurate unbiased sounding products with good spatial coverage that are used to generate consistent multi-year climate data sets to study the earth's interannual variability, climate processes, and possibly long-term trends. AIRS is a grating spectrometer with a number of linear arrays of detectors with each detector sensitive to outgoing radiation in a characteristic frequency ν_i , with a roughly Gaussian spectral band pass with half-width $\Delta\nu_i$ (spectral resolution) of roughly $\nu_i/1200$. AIRS contains 2378 spectral channels covering portions of the spectral region 650 cm^{-1} ($15.38\text{ }\mu\text{m}$) through 2665 cm^{-1} ($3.752\text{ }\mu\text{m}$), with corresponding spectral half-widths ranging from approximately 0.5 cm^{-1} to 2.2 cm^{-1} . The spectral sampling interval (except for the

existence of a few gaps) is $\nu_i/2400$, giving two AIRS channels per spectral half width. AIRS is accompanied by the temperature sounding 60 GHz microwave instrument AMSU-A. There is a 3x3 array of AIRS footprints within a given AMSU-A footprint, with spatial resolutions of 13 km and 45 km at nadir viewing for AIRS and AMSU respectively. Each AIRS footprint is referred to as a Field of View (FOV), and the AMSU-A footprint is referred to as a Field of Regard (FOR). AIRS retrievals of geophysical parameters are performed on a FOR basis.

CrIS/ATMS was launched on Suomi-NPP in October 2011 as part of a sequence of Low Earth Orbiting satellite missions under the “Joint Polar Satellite System” (JPSS). The future JPSS missions, J1 and J2, are currently scheduled for November 2016 and November 2021 launches. The J1 mission will be very similar to NPP, using the same spacecraft and instrument complement. CrIS² and ATMS are advanced infra-red and microwave atmospheric sounders that were designed as follow-ons to the AIRS and AMSU instruments flying on EOS Aqua. CrIS is an interferometer with similar spectral coverage and noise characteristics to those of AIRS. CrIS contains three spectral bands: band 1 covering 650 cm^{-1} to 1095 cm^{-1} ; band 2 covering 1210 cm^{-1} to 1750 cm^{-1} ; and band 3 covering 2155 cm^{-1} to 2550 cm^{-1} . Unlike a grating instrument which is characterized by a roughly constant resolving power, the “spectral resolution” of an interferometer is constant within a band, and it depends on the maximum Optical Path Displacement L of that band. As currently configured, $L = 0.8$ cm, 0.4 cm, and 0.2 cm for CrIS bands 1, 2, and 3 respectively. The spectral sampling interval of an interferometer is given by $1/2L$, corresponding to 0.625 cm^{-1} in band 1, 1.25 cm^{-1} in band 2, and 2.5 cm^{-1} in band 3. The intrinsic “spectral resolution” of an interferometer is not well defined because channel spectral response functions of an interferometer depend on the type of apodization used to transform the interferogram into the radiance domain, and unlike those of AIRS, the spectral response functions have side lobes which are apodization dependent. Barnett et al.³ show that use of a Hamming apodization function provides an optimum balance between minimizing the width of the central lobe of the spectral response function (which is a measure of spectral resolution) on the one hand, and the size of the spectral side lobes on the other. Using Hamming apodization, the full width at half maximum of the central lobe, which can be thought of as the spectral resolution in a band, is given by $0.9/L$, which corresponds to 1.112 cm^{-1} , 2.25 cm^{-1} , and 4.5 cm^{-1} for bands 1-3 respectively. Both the spectral sampling and “spectral resolution” of CrIS channels are roughly twice as coarse as those of corresponding AIRS channels.

Figure 1a shows an example of a cloud free AIRS brightness temperature spectrum computed for a tropical scene. The AIRS spectrum indicates the locations of channels used in different steps in the AIRS Science Team Version-6 retrieval algorithm⁴ currently operational at the Goddard DISC. Different sets of channels, shown in different colors, are used for different purposes as discussed later. Figure 1b shows the Hamming Apodized CrIS spectrum computed for the same scene and shows analogous sets of channels which we are using to analyze CrIS/ATMS data in an AIRS “Version-6 like” retrieval algorithm adapted for CrIS/ATMS. AIRS spectra have some gaps within a spectral region, while CrIS spectra are contiguous within a band. Figure 1 shows that the spectral coverages of AIRS and CrIS are similar to each other. AIRS extends further than CrIS in the longwave window region, with additional channels covering 1095 cm^{-1} to 1137 cm^{-1} ; CrIS extends further than AIRS in the water vapor band from 1614 cm^{-1} to 1750 cm^{-1} ; and AIRS extends further in the shortwave window region from 2550 cm^{-1} to 2667 cm^{-1} .

The Goddard DISC has generated AIRS/AMSU retrieval products, extending from September 2002 through real time, using the AIRS Science Team Version-6 retrieval algorithm. Level-3 gridded monthly mean values of these products, generated using AIRS Version-6, form a state of the art multi-year climate data set, which is expected to continue through 2022 and possibly beyond, as the AIRS instrument is extremely stable. AIRS Version-6 level-3 products include: surface skin temperature and surface spectral emissivity; atmospheric total precipitable water, total column ozone methane, and carbon monoxide; profiles of atmospheric temperature, water vapor, ozone, methane, and carbon monoxide; cloud heights and fractional cloud cover; and total Outgoing Longwave Radiation (OLR) and its spectral components. The AIRS Science Team has begun work on a further improved AIRS Version-7 algorithm, which will eventually be used to reprocess the entire AIRS data set. In the interim, we have been conducting research to optimize products derived from CrIS/ATMS observations using a scientific approach analogous to that currently used in the AIRS Science Team Version-6 algorithm.

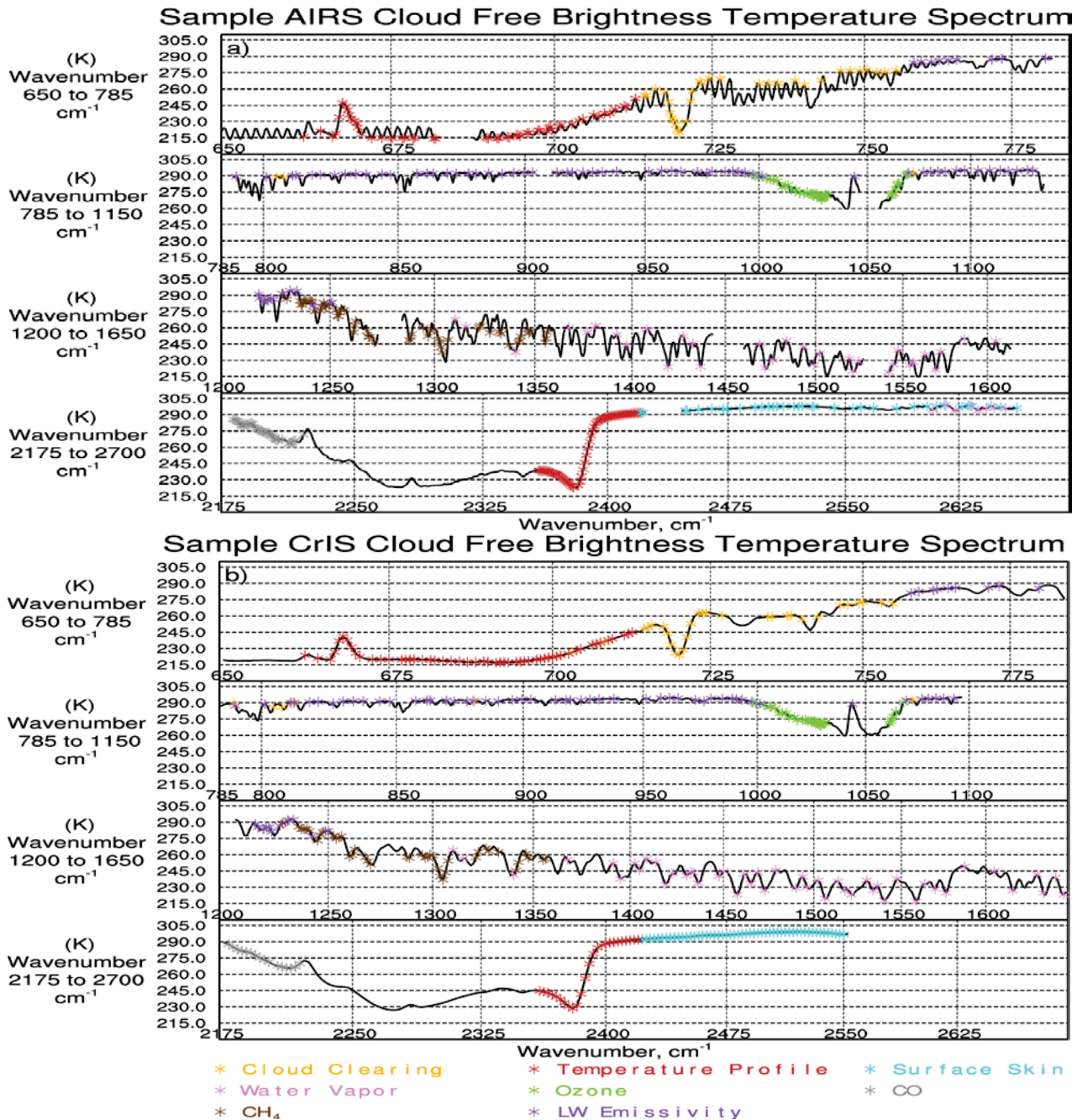


Figure 1. Sample AIRS and CrIS brightness temperature computed for a cloud free scene. The AIRS and CrIS channels we use in different steps in the retrieval process are indicated in the figure by different colored stars.

The goal of this research is to evaluate the degree to which monthly mean level-3 gridded products can be derived from CrIS/ATMS which will be compatible with, and of comparable quality to, those being generated operationally using AIRS/AMSU data, in order to assess the extent that CrIS/ATMS will provide a suitable follow-on to AIRS/AMSU from the climate perspective. It is essential that the assessment of the potential of CrIS/ATMS to provide an adequate continuation of AIRS level-3 climate data products be made utilizing a state of the art retrieval algorithm in the analysis of CrIS/ATMS radiances, along the lines of AIRS Version-6. NOAA is analyzing

CrIS/ATMS observations using two different retrieval algorithms, referred to as IDPS and NUCAPS. The IDPS algorithm was developed for NOAA and has heritage from an algorithm provided by industry. The NUCAPS algorithm⁵ was developed at NOAA and is based on earlier versions of the AIRS Science Team retrieval methodology. NOAA did not have climate related requirements for the analysis of CrIS/ATMS data, and neither algorithm is optimized for climate monitoring purposes. This paper contains a preliminary assessment of the suitability of Quality Controlled (QC'd) CrIS/ATMS retrievals we have thus far generated using an approach similar to Version-6, but not yet containing all of the upgrades contained in Version-6, for use in climate studies. This paper also includes such an assessment with regard to QC'd products generated by NOAA using the NUCAPS algorithm.

2. THE AIRS SCIENCE TEAM VERSION-6 RETRIEVAL ALGORITHM

The AIRS Science Team Version-6 retrieval algorithm builds on the AIRS Science Team pre-launch algorithm⁶, and on subsequent AIRS Science Team research. All versions of the AIRS Science Team retrieval algorithm are physically based and determine a set of geophysical parameters, X_j , such that radiances computed from the state X_j best match clear column radiances \hat{R}_i , where \hat{R}_i is a derived parameter representing the radiance channel i would have seen if the AMSU FOR, on which the AIRS retrieval is generated, were completely clear. Susskind et al.⁷ described the AIRS Science Team Version-4 retrieval algorithm which differed only slightly from the pre-launch algorithm. AIRS Version-4 introduced for the first time a QC concept that generated different QC flags for a given profile as a function of height, and also had separate QC flags related to surface skin temperature. The AIRS Science Team Version-5 retrieval algorithm⁸ contained many significant further improvements in retrieval methodology, the most important of which was the set of channels used to retrieve the atmospheric temperature profile $T(p)$. Both Version-5 and Version-6 follow cloud clearing theory^{9,10}, which states that 15 μm (660 cm^{-1}) CO_2 tropospheric sounding channels should not be used to retrieve $T(p)$ in a FOR, but rather should be used only to generate coefficients which provide \hat{R}_i for all channels in that FOR. The channels we use for cloud clearing are shown in yellow in Figure 1. We determine $T(p)$ using \hat{R}_i in 15 μm stratospheric sounding CO_2 channels and in 4.2 μm (2370 cm^{-1}) tropospheric sounding CO_2 channels. The channels we use to determine $T(p)$ are shown in red in Figure 1. Version-4 used channels in the entire 15 μm band for temperature sounding purposes and this was shown to be sub-optimal⁸. We also developed methodology in Version-5 to generate case-by-case, level-by-level, error estimates of $T(p)$, $\delta T(p)$, and to use thresholds of $\delta T(p)$ for QC purposes. The currently operational AIRS Version-6 retrieval algorithm contains additional significant improvements in retrieval methodology. Foremost among these is a major improvement in the methodology we use to determine surface skin temperature, T_s , surface spectral emissivity, $\varepsilon(\nu)$, and surface spectral bi-directional reflectance $\rho_{sw}(\nu)$. In the AIRS Version-6 surface skin temperature retrieval step, we simultaneously determine T_s , $\varepsilon_{sw}(\nu)$, and $\rho_{sw}(\nu)$ using only the shortwave window channels between 2420 cm^{-1} and 2664 cm^{-1} , which are shown in light blue in Figure 1, along with the 24 highest frequency (red) channels, which we also use in the $T(p)$ retrieval step. Surface longwave spectral emissivity $\varepsilon_{lw}(\nu)$ is determined in a subsequent step in Version-6 using window channels between 758 cm^{-1} and 1250 cm^{-1} , shown in purple in Figure 1. This approach results in significantly improved surface parameter retrievals compared to Version-5⁴, in which all surface parameters were determined together in a single step using both longwave and shortwave window channels. In Version-6, the water vapor profile $q(p)$ retrieval step uses \hat{R}_i in channels (pink stars) in the spectral ranges 1310 cm^{-1} to 1605 cm^{-1} and 2608 cm^{-1} to 2656 cm^{-1} ; the $\text{O}_3(p)$ retrieval uses \hat{R}_i in channels (green stars) between 997 cm^{-1} and 1069 cm^{-1} ; the $\text{CO}(p)$ retrieval uses \hat{R}_i in channels (gray stars) between 2181 cm^{-1} and 2221 cm^{-1} ; and the $\text{CH}_4(p)$ retrieval uses \hat{R}_i in channels (brown stars) between 1220 cm^{-1} and 1356 cm^{-1} .

We use analogous sets of channels in our analysis of CrIS/ATMS data. AIRS resolves CO_2 absorption lines in the 15 μm band, and the locations of the AIRS channels we use for determining $T(p)$ and for cloud clearing lie primarily between the CO_2 lines. CrIS does not resolve these lines, but the CrIS 15 μm channels we use for these purposes are located at roughly the same frequencies as those we use for AIRS. A potentially significant limitation of CrIS is that the shortwave band extends to only 2550 cm^{-1} , and this degrades the surface parameter retrieval somewhat compared to AIRS. Version-6 contains another significant improvement over Version-5 in that the initial guess is generated by using Neural-Net methodology^{11,12} in place of the previously used regression approach. As of this writing, we have not yet successfully implemented the Neural-Net methodology to generate the first guess for use with CrIS/ATMS data.

Our current CrIS/ATMS retrieval algorithm, which we refer to as CrIS Version-5.70, is otherwise analogous to AIRS Version-6 but uses a regression based start-up state as opposed to the Neural-Net start-up state used in AIRS Version-6.

We plan to implement a Neural-Net start-up for CrIS/ATMS when it is ready. We have generated the CrIS and ATMS tuning coefficients and regression coefficients used in the retrieval algorithm based on observations taken on July 10, 2012 and September 14, 2012. Tuning coefficients represent systematic errors between observed and computed radiances for channel i , and radiances computed for channel i in the retrieval process are adjusted accordingly. We also generated appropriate CrIS/ATMS error estimate coefficients and error estimate thresholds based on observations for those two days. We use all these coefficients in the analysis of CrIS/ATMS retrievals for all subsequent time periods.

2.1 Steps in the Version-6 retrieval algorithm

Retrievals of all geophysical parameters are physically based and represent states $X_{j,c}$ derived for case c that best match a set of clear column radiances $\hat{R}_{i,c}$ for the subset of AIRS channels i used in that step in the retrieval process. \hat{R}_i for any channel is given by a channel independent linear combination of the observations in that channel in each of the nine AIRS FOV's within the FOR on which the solution is being obtained. Retrievals of geophysical parameters are performed sequentially, that is, only a subset of the geophysical parameters within the state X_j are modified in a given step. The steps in the Version-6 physical retrieval process are as follows: A Neural-Net start-up procedure is used to generate the initial state X^o . Initial clear column radiances \hat{R}_i^o in a FOR are generated for all channels i using the initial state X^o and cloud-clearing coefficients for that FOR which are generated using observed radiances in the cloud clearing channels in each of the nine FOV's in the FOR⁶. The state X^o is also used as the initial guess to the physical retrieval process in which AIRS/AMSU observations are used to retrieve sequentially: a) T_s , ϵ_{sw} , and ρ_{sw} ; b) $T(p)$; c) atmospheric moisture profile, $q(p)$; d) $\epsilon_{lw}(v)$; e) atmospheric ozone profile, $O_3(p)$; f) atmospheric CO profile, $CO(p)$; and g) atmospheric CH₄ profile, $CH_4(p)$. Cloud properties and OLR are then computed after the retrieval is completed so as to be consistent with observed radiances R_i and those computed from the final retrieved state X . These steps are done sequentially, solving only for the variables to be determined in each retrieval step while using previously determined variables as fixed. The objective in each step (a-g) is to find solutions which best match \hat{R}_i for the subset of channels selected for use in that step, bearing in mind the channel noise covariance matrix. Steps a-g are ordered so as to allow for selection of channels in each step which are primarily sensitive to variables to be determined in that step or determined in a previous step, and are relatively insensitive to other parameters. Separation of the problem in this manner allows for the problem in each step to be made as linear as possible. The steps used in CrIS Version-5.70 are otherwise identical but use a regression based start-up state X^o .

3. COMPARISON OF RESULTS OBTAINED USING AIRS VERSION-6, CrIS VERSION-5.70, and NUCAPS

This section compares AIRS results we derived using the AIRS Version-6 retrieval algorithm, henceforth called AIRS, CrIS results we derived using CrIS Version-5.70, henceforth called CrIS; and CrIS results derived by NOAA using the NOAA Unique CrIS/ATMS Processing System (NUCAPS) algorithm, henceforth called NUCAPS. NOAA generated their own set of CrIS/ATMS tuning coefficients and regression coefficients for their use in their CrIS/ATMS NUCAPS retrieval system. NUCAPS produces many of the same type of products which are generated using AIRS Version-6. We show results for June 22, 2013 for demonstrative purposes. The two black horizontal lines in Figure 2 are at 500 mb and 700 mb respectively. Figure 2 shows $T(p)$ statistics of the differences of QC'd AIRS and CrIS retrievals from a collocated ECMWF 3 hour forecast, which we take as "truth", for a global ensemble of cases on June 22, 2013. Panel (a) shows the percentage of QC'd cases accepted as a function of height; panel (b) shows RMS differences of QC'd 1 km layer mean temperatures from a collocated ECMWF 3-hour forecast considered as "truth"; and panel (c) shows biases of QC'd 1 km layer mean differences from ECMWF. We refer to differences from ECMWF as "errors". Version-6 QC methodology is based on use of thresholds of error estimates for a given state and is described in Olsen et al¹³. AIRS Version-6 and CrIS Version-5.70 each designate two characteristic pressures for each temperature profile, p_{best} and p_{good} , to be used for Data Assimilation (DA) purposes and for the generation of level-3 products used for climate studies respectively. DA statistics include all cases down to p_{best} and climate statistics

include all cases down to p_{good} , which must be greater than or equal to p_{best} . Version-6 and Version-5.70 both use two different sets of $\delta T(p)$ QC thresholds to define p_{best} and p_{good} respectively. A tight set of DA $\delta T(p)$ thresholds, optimized for DA purposes, was designed to derive p_{best} so as to achieve 1 km layer mean RMS errors for accepted cases on the order of 1K throughout the troposphere, and a substantially looser Climate set of $\delta T(p)$ thresholds was

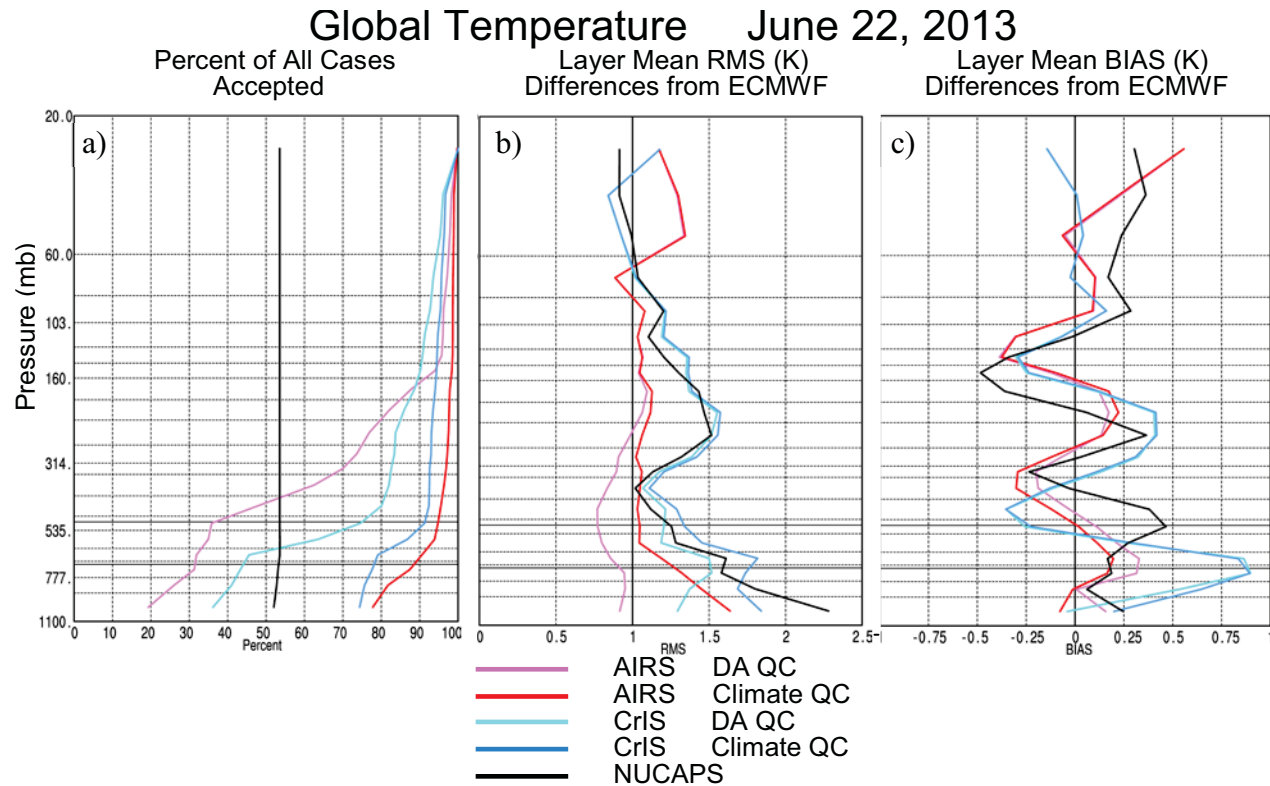


Figure 2. Global QC'd 1 km layer mean temperature profile statistics for June 22, 2013 for different retrievals and different QC thresholds. a) Percent of all cases accepted; b) 1 km layer mean RMS differences from colocated ECMWF 3-hour forecast; c) 1 km layer mean bias from ECMWF.

optimized for climate purposes. Climate QC thresholds are used to derive p_{good} , down to which $T(p)$ products are included in the generation of level-3 climate data sets. Climate QC thresholds were designed so as to maximize the spatial coverage of accepted retrievals while still maintaining reasonable overall accuracy. The dark red and dark blue lines in Figure 2 show statistics for AIRS and CrIS results using their appropriate Climate QC thresholds, and the pink and light blue lines show results using their DA QC thresholds. The yields of AIRS retrievals with Climate QC are extremely high throughout the atmosphere, with a value greater of 95% at 500 mb and about 78% at the surface. Global mean RMS errors of AIRS retrieved 1 km layer mean temperatures using Climate QC are essentially 1K down to 500 mb, and grow to about 1.7K near 1000 mb. Achievement of this very high yield and high accuracy is extremely valuable in the generation of highly representative level-3 climate data sets. RMS errors of AIRS retrievals with DA Quality Control are less than 1K throughout the troposphere, which is a required result from the perspective of assimilation of QC'd values of $T(p)$ to improve forecast skill¹⁴. The global yields of tropospheric AIRS retrievals using DA QC are considerably lower than those using Climate QC, but this is less important from the DA perspective than the high accuracy of the ensemble of accepted retrievals. CrIS yields at 500 mb and 1000 mb with Climate QC are somewhat lower than those of AIRS, but are still very high with values of 92% and 74% respectively. CrIS $T(p)$ errors with Climate QC are larger than those of AIRS, but are still very good and better than those achieved with AIRS using the AIRS Version-5 retrieval algorithm⁹. CrIS errors with DA QC are somewhat smaller than with Climate QC but with a significant reduction in yield. A further tightening of CrIS $\delta T(p)$ QC thresholds for DA purposes did not significantly reduce RMS errors beyond what is shown in Figure 2. CrIS results should improve when we run and

optimize CrIS retrievals using the Neural-Net start-up option as is done in AIRS Version-6. Some research and development is still needed to achieve this.

Figure 2 also contains analogous results for CrIS/ATMS retrievals run by NOAA using the NUCAPS algorithm, shown in black. The NUCAPS retrieval algorithm is an AIRS Science Team-like retrieval algorithm but does not contain some of the important upgrades incorporated in AIRS Version-5 and Version-6. Some differences in NUCAPS from Version-6 are as follows: 1) 15 μm CO_2 tropospheric temperature sounding channels are included in the temperature profile retrieval step; 2) longwave and shortwave window channels are used simultaneously in the determination of all surface skin parameters; 3) a regression based start-up system is used in place of Neural-Net; and perhaps most significantly, 4) a single QC flag, indicative of mid-tropospheric temperature quality, is used for all retrieved parameters, including surface skin temperature. The global yield of NUCAPS retrievals on this day is about 53%. NUCAPS $T(p)$ RMS errors are slightly better than those of CrIS Version-5.70 with Climate QC down to about 850 mb, but the NUCAPS yield is much lower throughout the atmosphere.

Figure 3 shows counts of Quality Controlled Ocean Surface Skin Temperatures (SST's) over the latitude range 50°N to 50°S as a function of the difference between T_s and ECMWF “truth” for the same day. The counts of accepted AIRS retrievals are shown in red and pink using Climate T_s QC and DA T_s QC thresholds respectively. Analogous statistics for CrIS are shown in dark blue and light blue, and NUCAPS results are shown in black. The AIRS and CrIS level-3 ocean surface skin temperature products we generate include all cases passing Climate QC, and the identical NUCAPS level-3 product we generate includes all ocean cases passing the single NUCAPS QC flag. We use a different approach in Version-6 to generate level-3 T_s products over land and ice, in which T_s for a given case is included as long as p_{good} is at most 1.5 km above the surface. As with ocean skin temperatures, the ensemble of cases we include in the generation of the NUCAPS level-3 T_s product over land is identical to that used for $T(p)$ at all levels. Figure 3 contains statistics for each set of QC'd retrievals showing the mean difference from ECMWF, the standard deviation (STD) of the ensemble differences, the percentage of all possible cases included in the QC'd ensemble, and the percentage of all accepted cases with absolute differences from ECMWF of more than 3K from the mean difference, which we refer to as outliers. AIRS T_s with Climate QC accepts 50.6% of all cases, with a mean difference from ECMWF of -0.24K and a STD of 0.95K, and contains 1.85% outliers. With tighter DA T_s QC thresholds, the

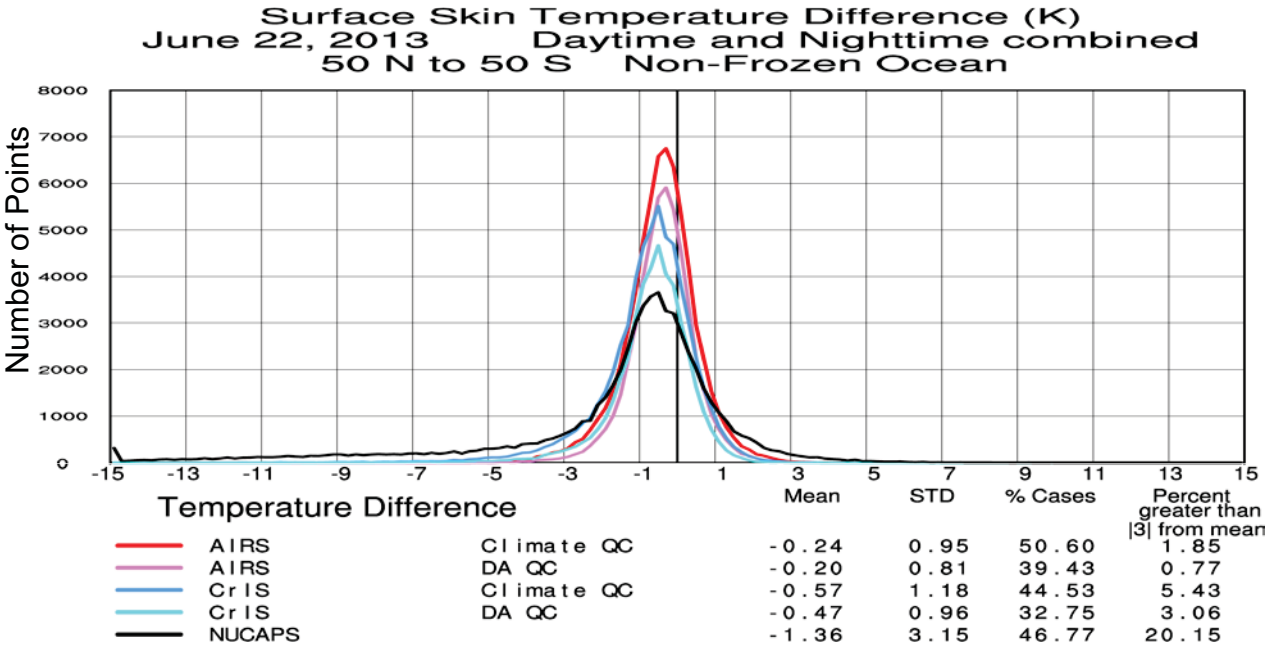


Figure 3. Histograms of the differences of QC'd ocean surface skin temperatures from ECMWF “truth” for different retrievals and different QC thresholds on June 22, 2013.

AIRS yield drops to 39.43%, and the bias and STD drop to -0.20K and 0.81K respectively, with a remarkably low outlier value of 0.77%. CrIS T_s statistics are also very good, and are better than what was achieved in analysis of AIRS data using Version-5⁸. They are considerably poorer than what is achieved for AIRS with regard to yield, mean error, STD, and % outliers, however. Note that CrIS T_s with DA QC has errors that are poorer than those of AIRS with Climate QC, and has a yield of 32.75% as compared to 50.60% for AIRS. CrIS statistics should improve somewhat when the Neural-Net start-up system is implemented, but we believe that the capability of CrIS to produce accurate surface skin temperatures under cloudy conditions is hampered by not having shortwave window channels beyond 2550 cm^{-1} , especially during the day in which shortwave window radiances are affected considerably by solar radiation reflected by the surface. NUCAPS QC'd SST results are extremely poor. The 46.77% yield is high, almost as high as that of AIRS with Climate QC, but the yield of accurate retrievals is low. QC'd NUCAPS retrievals contain 20% outliers, most of them being very cold. This poor performance is a result of the fact that the NUCAPS QC flag, which is based on expected good mid-tropospheric temperature profile performance, is not necessarily indicative of retrieval performance near the surface, where significant amounts of low cloud cover could exist and seriously degrade surface skin temperature retrievals.

Figures 4a, 4b, and 4c show level-3 surface skin temperature products we generated depicting the spatial distributions, on a 1° latitude by 1° longitude grid, of retrieved surface skin temperatures for ascending (1:30 PM local time) orbits for AIRS, CrIS, and NUCAPS respectively. Level-3 products contain the average value of all accepted retrievals falling within the grid box. Warmer temperatures are shown in reds, browns, and yellow; and colder temperatures are shown in blue and shades of purple. Grid points in which no QC'd retrievals were produced are indicated as gray. The caption beneath each figure indicates the cosine latitude area weighted global mean temperature, the Standard Deviation (STD) of the grid point temperatures, and the percentage of the grid points which contain a product, that is, which are not shown in gray. There are two different reasons for having no data in a grid box: 1) all observations by the satellite in that grid box have failed the T_s QC procedure; or 2) there were no satellite observations in that grid box as a result of gaps in the orbital coverage of the earth. Both AIRS and CrIS scan $\pm 49.5^\circ$ from nadir along the orbit track, but CrIS is carried on Suomi-NPP, flying in an 824 km orbit, and AIRS is carried on Aqua, flying in a 705 km orbit. For this reason, the orbital swath of CrIS is wider than that of AIRS, and the gaps in CrIS coverage between orbits are narrower. This feature is apparent in Figure 4, in which the widths of the orbit gaps near the equator in Figures 4b and 4c, showing CrIS results, are identical to each other, and narrower than those of AIRS shown in Figure 4a. The spatial grid point coverages of AIRS and CrIS are essentially identical to each other, 72.02% and 72.05% respectively, and the coverage of NUCAPS T_s retrievals is substantially higher, at 80.75%. Rejected retrievals tend to cluster together spatially, so observations falling in a given grid box can all be rejected, and even more significantly, this phenomenon can occur in large contiguous areas of adjacent grid boxes.

Many large gaps in retrieval coverage are apparent in Figures 4a-4c. Gaps resulting from areas of rejected retrievals are in similar locations for AIRS and CrIS, especially over ocean. NUCAPS gaps over ocean sometimes occur in different spatial regions as compared to AIRS and CrIS. NUCAPS also has coverage gaps in some areas of hot (yellow) land such as the western Sahara Desert and southwestern United States. The spatial coverage of QC'd NUCAPS T_s retrievals is identical to that obtained for any other NUCAPS field because there is only a single NUCAPS QC flag. AIRS and CrIS T_s retrievals over non-frozen ocean are accepted and included in the level-3 product if T_s retrievals pass Climate QC, with statistics shown in Figure 3. Over land, AIRS and CrIS T_s retrievals are accepted and included in the level-3 product if p_{good} is at most 1.5 km above the surface.

Figures 4d, 4e, and 4f show values of AIRS minus ECMWF T_s , CrIS minus ECMWF T_s , and NUCAPS minus ECMWF T_s , respectively. Results are shown only for oceanic grid points between 50°N and 50°S . The ECMWF T_s product over land is not a good measure of truth, both because T_s over land is not well known on the one hand, and even more significantly, T_s over land changes very rapidly in space and time. White in Figures 4d-4f means grid point T_s values agree with ECMWF to within $\pm 0.5\text{K}$, reds means the retrieval is warmer than ECMWF, and blues and yellows mean the retrieval is colder than ECMWF. Area weighted grid point statistics, showing the mean T_s difference from ECMWF, the standard deviation of the grid point T_s differences from ECMWF, and the spatial correlations of retrieved T_s with that of ECMWF, are indicated in Figures 4d-4f. The AIRS level-3 oceanic T_s product agrees best with ECMWF, with a mean difference of -0.38K, a spatial standard deviation of 1.01K, and a spatial correlation of 0.99. AIRS values between 30°N and 30°S are of particularly high quality and contain only very small gaps. There are

larger gaps over ocean at higher latitudes where AIRS T_s retrievals have been rejected, such as in the region between 35°N and 50°N off the east coast of Asia and in a region southwest of Canada. These two areas are outlined by brown and red rectangles respectively. T_s retrievals in these areas are for the most part also rejected in Version-5.70 CrIS, and to some extent are rejected in NUCAPS as well. The NUCAPS level-3 T_s product does contain some extremely poor accepted values of T_s in these areas, however. These show up in yellow in Figure 4f, indicative of errors as large as -7.5K. NUCAPS T_s also has very large negative errors in the region between 15°N to 35°N and 135°W to 120°W, outlined in black, for which T_s retrievals were for the most part rejected in CrIS Version-5.70. AIRS Version-6 did not reject T_s retrievals in this area, and the accepted AIRS retrievals in this area are of high quality.

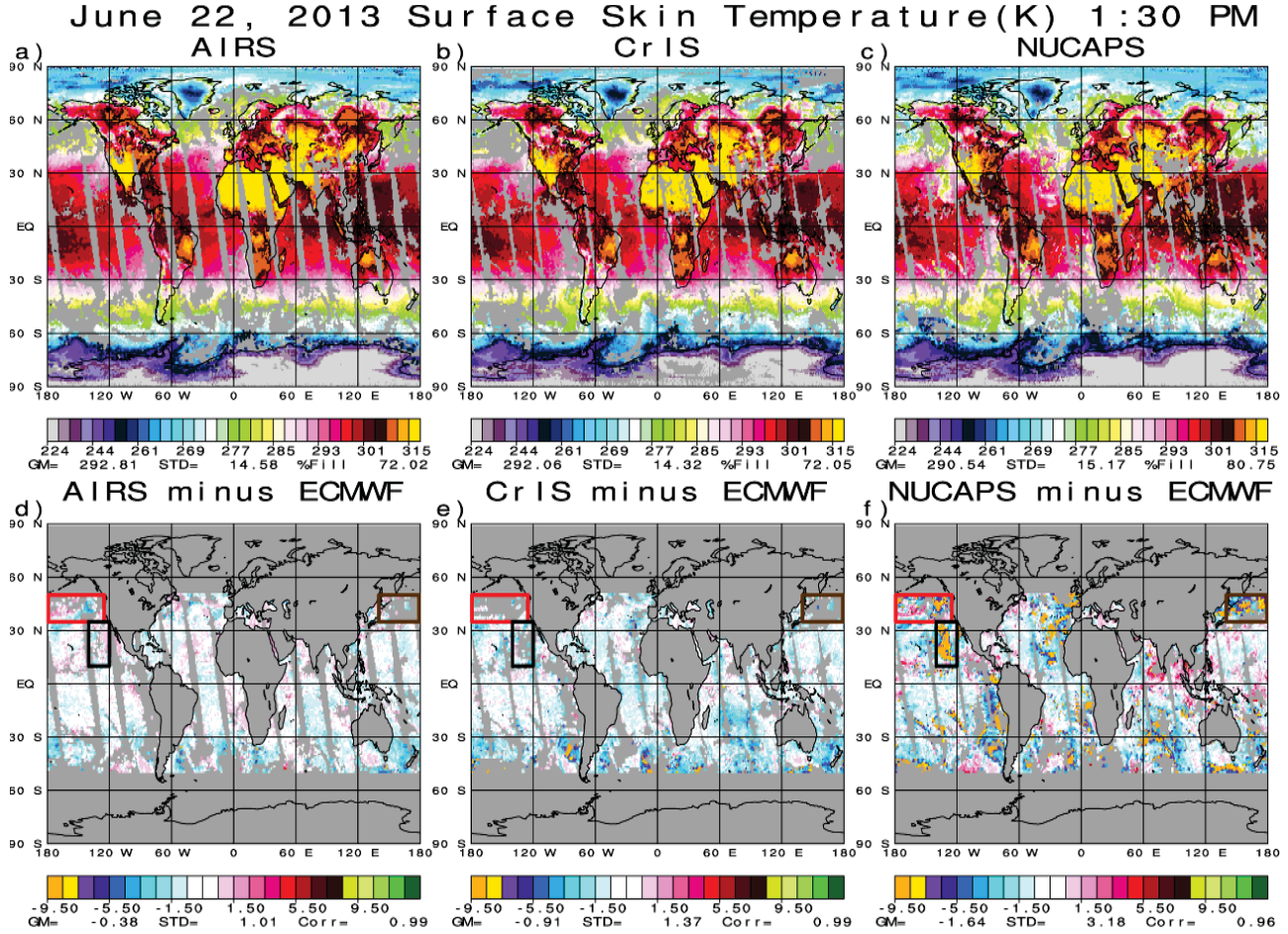


Figure 4. Surface skin temperature level-3 products, on a 1° x 1° spatial grid, for ascending orbit on June 22, 2013. Gray means no data in a grid box. Global retrieved surface skin temperatures are shown in a-c. Differences from ECMWF for non-frozen ocean 50°N -50°S are shown in d-f.

Figures 5a-5f are analogous to Figures 4a-4f, but show total precipitable water (cm), which we call W_{TOT} . The spatial coverage of NUCAPS QC'd W_{TOT} is identical to that of T_s because the same QC flag is used. The spatial covers of AIRS and CrIS W_{TOT} are both substantially higher than those of T_s , because the AIRS and CrIS QC methodology used for W_{TOT} is not as stringent as that used for T_s , especially over ocean. Figure 5 shows that AIRS and CrIS W_{TOT} level-3 products have almost complete spatial coverage over both land and ocean. Areas of contiguous level-3 gaps are small for both AIRS and CrIS, and smaller for AIRS than for CrIS. White areas in Figures 5d-5f indicate agreement of W_{TOT} with ECMWF to within ± 0.1 cm. Reds mean retrieved W_{TOT} is larger than ECMWF, and blues mean it is lower. Unlike with skin temperature, more AIRS and CrIS grid points contain accepted values of W_{TOT} as compared to NUCAPS.

Figures 5d–5f show that Version-5.70 CrIS W_{TOT} retrievals agree better with ECMWF than do Version-6.0 AIRS retrievals, especially over ocean. This improvement in performance of CrIS W_{TOT} retrievals, as compared to that of AIRS, is primarily a result of CrIS being accompanied by the microwave sounder ATMS, which performs better than the AMSU-A microwave sounder accompanying AIRS, especially with regard to sensitivity to W_{TOT} over ocean. Statistics for (NUCAPS minus ECMWF) W_{TOT} , generated for a smaller spatial ensemble of cases, are poorer than those for (CrIS minus ECMWF) W_{TOT} , with a standard deviation of 0.33 cm, and a spatial correlation of 0.96, as compared to 0.26 cm and 0.99 for CrIS.

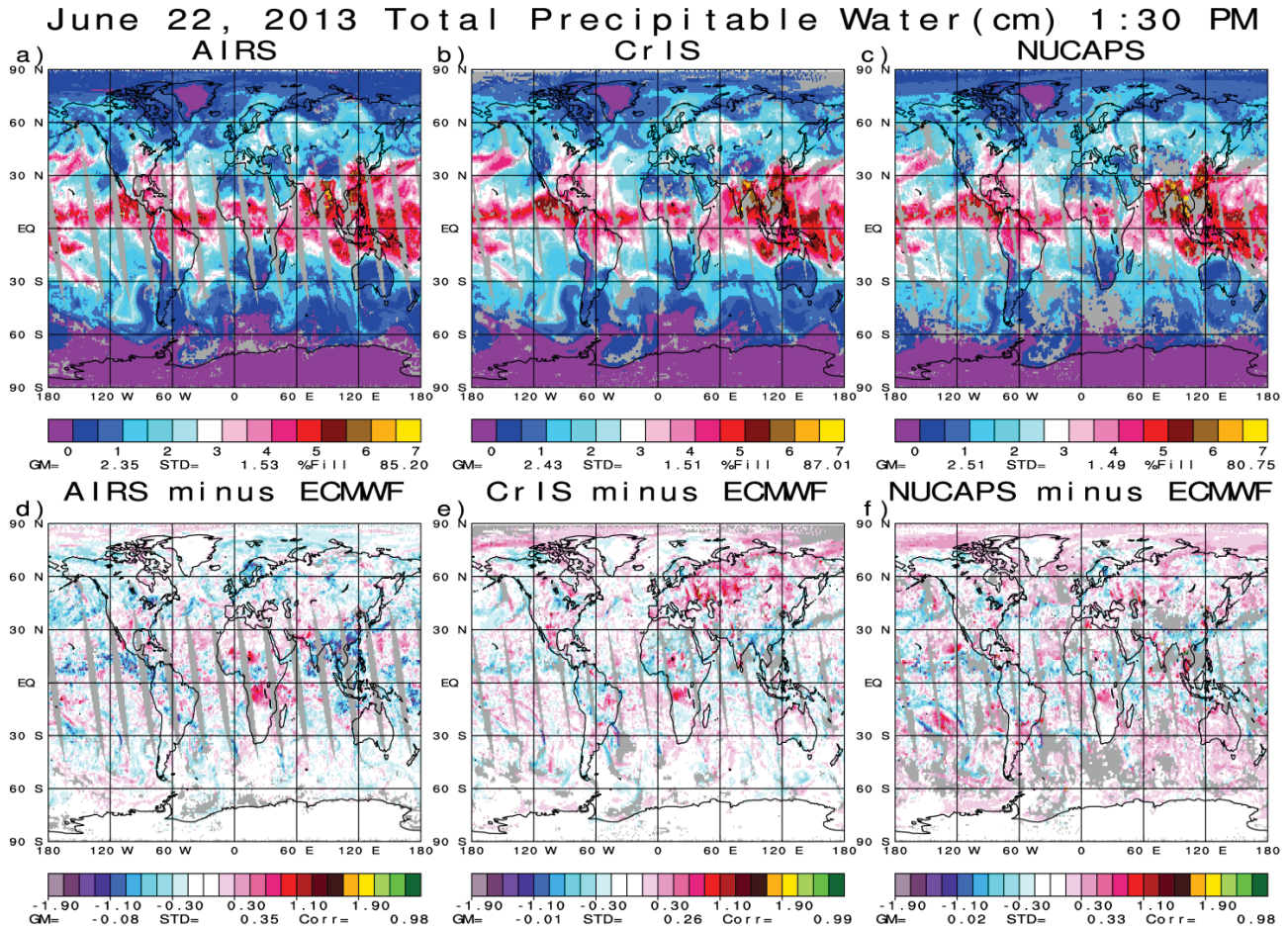


Figure 5. Global total precipitable water (cm) level-3 products for ascending orbits on June 22, 2013. Retrieved values are shown in a-c, and differences from ECMWF are shown in d-f.

Figures 6a-6f are analogous to those shown previously, but for 500 mb temperature $T(500)$. White areas in Figures 6e-6f indicate agreement of $T(500)$ with ECMWF to within $\pm 0.5K$. Global mean statistics showing agreement of 1 km layer mean temperature with ECMWF were presented in Figure 2. Figure 6 refers to values, and differences from ECMWF, of retrieved temperature at a single pressure level. Figure 2b showed that the RMS difference of 1 km layer mean NUCAPS temperature from ECMWF is about the same as that of Version-5.70 CrIS with DA QC, and is somewhat lower (better) than that of Version-5.70 CrIS with Climate QC. The percent of accepted NUCAPS retrievals at 500 mb (54%) is considerably lower than that accepted by Version-5.70 CrIS using DA QC (75%), and even more so using Climate QC (92%). The main interest of this paper is the potential suitability of CrIS for the continued generation of accurate climate data records after either the eventual failure of AIRS or retirement of

the Aqua satellite. From this perspective, the level-3 spatial plots using Climate QC, which are presented in Figures 4-6, are most relevant.

Figures 6a-6c show that at 500 mb, the AIRS level-3 $T(500)$ product has essentially complete grid point coverage, other than for those grid points lying in the gaps between orbits. CrIS level-3 $T(500)$ spatial coverage is also essentially complete, and contains smaller orbit gaps as discussed previously. June 22, 2013 is marked by significant areas containing intrusions of cold Antarctic air into southern hemispheric mid-latitudes, up to almost 30S. These features are well observed in both the AIRS and CrIS level-3 500 mb temperature product. Spatial coverage of the NUCAPS level-3 $T(500)$ product is of course identical to those of NUCAPS T_s and W_{TOT} . It is extremely important to note that for the most part, soundings in the areas containing these cold air intrusions have been rejected by the NUCAPS processing system, and show up as gray in Figure 6c.

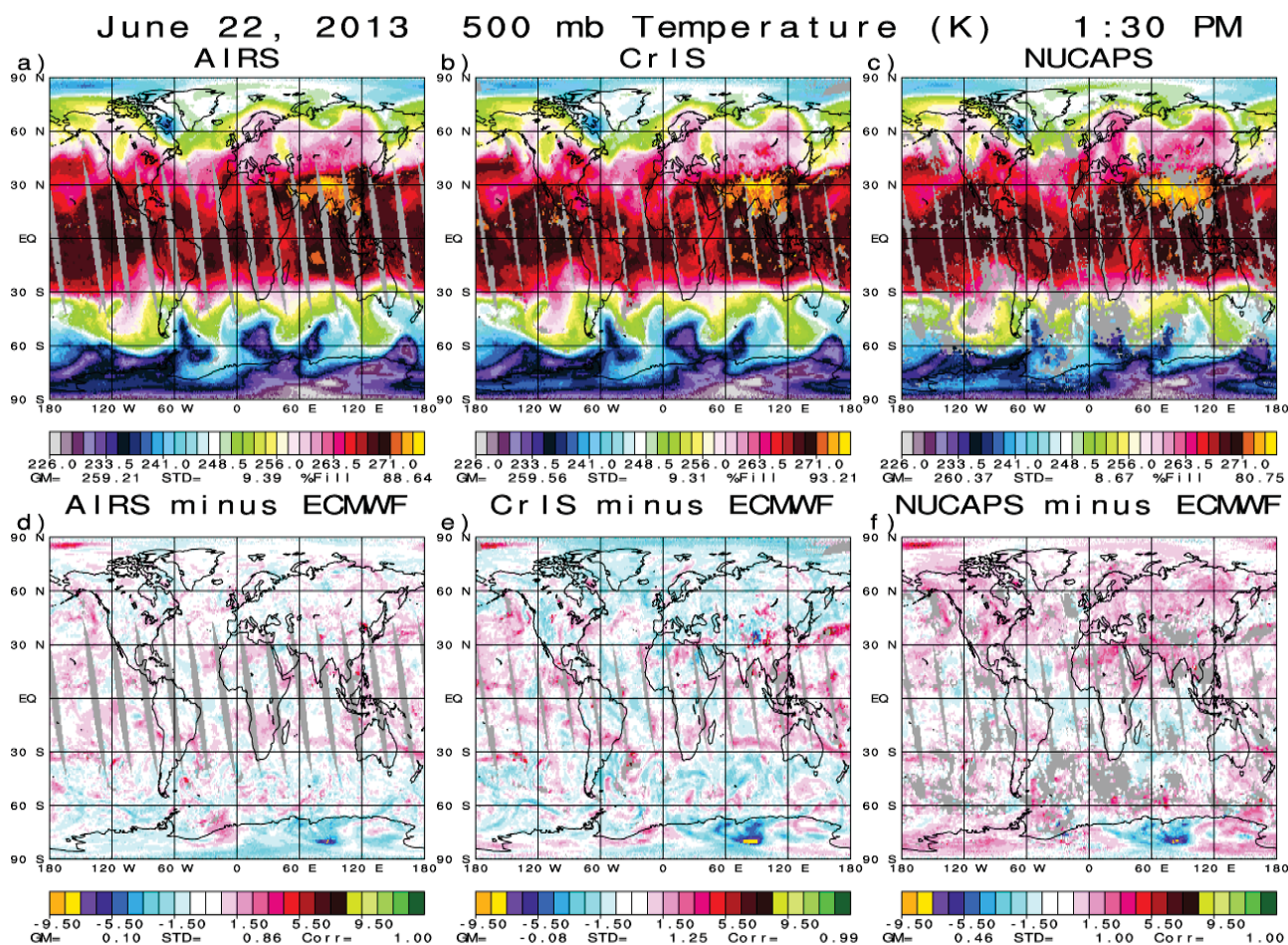


Figure 6. Global 500 mb temperature level-3 products for ascending orbits on June 22, 2013. Retrieved values are shown in a-c, and differences from ECMWF are shown in d-f.

The accepted NUCAPS soundings are more accurate than those of CrIS in the sense that the spatial standard deviation of the errors is smaller in NUCAPS than in CrIS, albeit with a positive bias compared to ECMWF, as shown in Figures 6d and 6e. This does not tell the whole story, however. The rejection of large contiguous cold air mass areas, which move from day to day, can have a significant deleterious effect on the generation of a monthly mean product if they are consistently excluded from the monthly mean product.

Figures 7a-7f are analogous to Figure 6a-6f, but are for retrieved 100 mb temperature, which is in the stratosphere. AIRS QC'd 100 mb temperatures have essentially complete spatial coverage. CrIS 100 mb temperature spatial coverage is also almost complete, but with some small spatial gaps near 10°N. NUCAPS 100 mb temperature spatial coverage is identical to that shown previously. NUCAPS 100 mb temperature has somewhat larger spatial gaps near 10°N than does CrIS. More significantly, not only does NUCAPS reject many retrievals in the areas between 30°S and 65°S that contain locally cold 500 mb temperatures, these same rejected areas contain locally warm temperatures at 100 mb. As with regard to 500 mb, rejecting locally warm areas, which move in time, can have a deleterious affect not only on monthly mean 100 mb temperatures if such warm areas are preferentially rejected, but also on retrieved monthly mean lapse rates between 500 mb and 100 mb. Statistically, NUCAPS 100 mb temperatures agree slightly better with ECMWF than do those of CrIS in the Standard Deviation sense. Both CrIS and NUCAPS 100 mb temperatures show a warm bias compared to ECMWF. This warm bias does not occur in AIRS 100 mb temperatures.

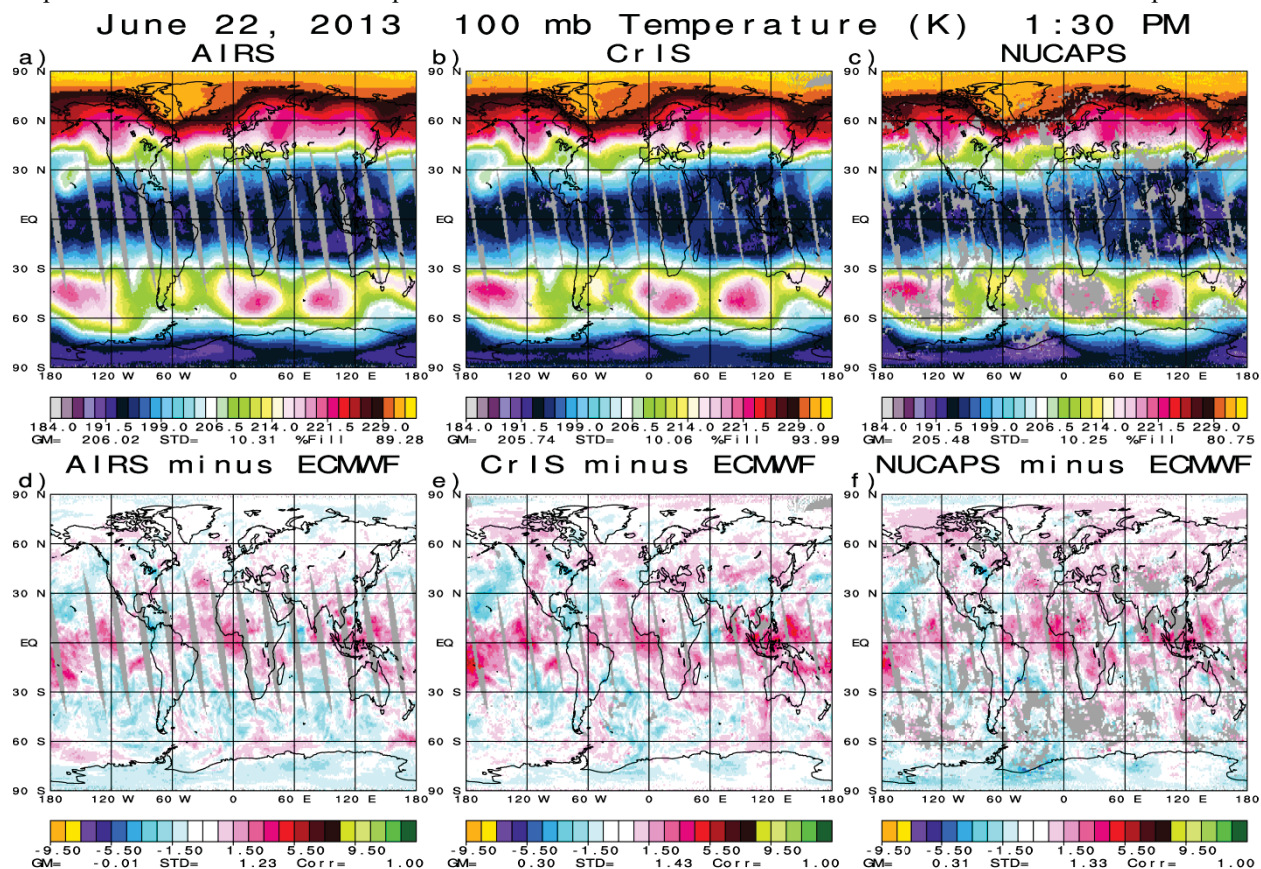


Figure 7. Global 100 mb temperature level-3 products for ascending orbits on June 22, 2013. Retrieved values are shown in a-c, and differences from ECMWF are shown in d-f.

4. SUMMARY

The main objective of this research is to assess whether CrIS/ATMS is an adequate replacement for AIRS/AMSU from the perspective of continued generation of accurate long term climate data records, or if improved instruments should be developed for future flight. We have been conducting research to optimize products derived from CrIS/ATMS observations using a scientific approach analogous to the currently operational state-of-the-art AIRS Science Team Version-6 retrieval algorithm. Our latest research uses Version-5.70 of the CrIS/ATMS retrieval algorithm, which is otherwise analogous to AIRS/AMSU Version-6, but does not yet contain the benefit of use of a Neural-Net first guess start-up system which significantly improved AIRS results in Version-6. Based on very limited results obtained on a single day, Version-5.70 CrIS/ATMS temperature profile and surface skin temperature retrievals

are of very good quality, and are better than AIRS Version-5 retrievals, but are still significantly poorer than those of AIRS Version-6. CrIS/ATMS retrievals should improve when a Neural-Net start-up system is ready for use.

We also examined CrIS/ATMS retrievals generated by NOAA using their NUCAPS retrieval algorithm, which is based on earlier versions of the AIRS Science Team retrieval algorithms. We show that the NUCAPS algorithm as currently configured is not well suited for climate monitoring purposes, at least in part because the NUCAPS Quality Control methodology, which provides only a single QC flag for use with all products, is too loose with regard to ocean surface skin temperatures, and too tight with regard to mid-tropospheric and stratospheric temperatures.

In the future, we plan to implement the Neural-Net start-up capability into our CrIS/ATMS retrieval algorithm, and after optimization, we will run what we will call Version-6 CrIS/ATMS retrievals for a number of consecutive months and compare monthly mean CrIS level-3 products with those of AIRS Version-6, as well as with those of NUCAPS. We will also compare level-3 Version-6 CrIS and NUCAPS results for all products with those of AIRS Version-6, in terms of inter-month differences, and better yet, interannual differences if this is practical.

REFERENCES

- [1] Pagano, T. S., Aumann, H. H., Hagan, D. E., and Overoye, K., "Prelaunch and in-flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS)," IEEE Trans. Geoscience and Remote Sensing, 41, 265-273, DOI: 10.1109/TGRS.2002.808324 (2003).
- [2] Glumb, R.J., Jordan, D.C., and Predina, J.P., "Crosstrack infrared sounder (CrIS)," Proc. of SPIE 4131, Infrared Spaceborne Remote Sensing VIII, 108-119, DOI:10.1117/12.406538 (2000).
- [3] Barnet, C.D., Blaisdell, J.M., and Susskind, J., "Practical methods of rapid and accurate computation of interferometric spectra for remote sensing applications," IEEE Trans. Geoscience and Remote Sensing, 38, 169-183 (2000).
- [4] Susskind, J., Blaisdell, J.M., and Iredell, L., "Significant advances in the AIRS Science Team Version-6 retrieval algorithm," Proc. of SPIE 8510, Earth Observing Systems XVII, 85100U ; DOI: 10.1117/12.929953 (2012).
- [5] Gambacorta, A., Barnet, C.D., Wolf, W.W., King, T.S., Maddy, E.S., Nalli, N.R., Zhang, K., Xiong, X., and Goldberg, M., "The NOAA Unique CrIS/ATMS Processing System (NUCAPS): algorithm description and preliminary validation," BAMS, in submission (2013).
- [6] Susskind, J., Barnet, C.D., and Blaisdell, J.M., "Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds," IEEE Trans. Geoscience and Remote Sensing, 41, 390-409, DOI: 10.1109/TGRS.2002.808236 (2003).
- [7] Susskind, J., Barnet, C., Blaisdell, J., Iredell, L., Keita, F., Kouvaris, L., Molnar, G., and Chahine, M., "Accuracy of geophysical parameters derived from atmospheric infrared sounder/advanced microwave sounding unit as a function of fractional cloud cover," J. Geophys. Res., 111, D09S17, DOI:10.1029/2005JD006272 (2006).
- [8] Susskind, J., Blaisdell, J.M., Iredell, L., and Keita, F., "Improved temperature sounding and quality control methodology using AIRS/AMSU data: The AIRS Science Team Version-5 retrieval algorithm," IEEE Trans. Geoscience and Remote Sensing, 49, 883-907, DOI:10.1109/TGRS.2010.2070508 (2011).
- [9] Chahine, M., "Remote sensing of cloudy atmospheres. I. The single cloud layer," J. Atmos. Sci., 31, 233-243 (1974).
- [10] Chahine, M., "Remote sounding of cloudy atmospheres. I. The single cloud layer," J. Atmos. Sci., 31, 744-757 (1977).

- [11] Tao, Z., Blackwell, W.J., and Staelin, D.H., "Error variance estimation for individual geophysical parameter retrievals," IEEE Trans. Geoscience and Remote Sensing, 51, 1718-1727, DOI: 10.1109/TGRS. 2012.2207728 (2013).
- [12] Blackwell, W.J., "Neural network Jacobian analysis for high-resolution profiling of the atmosphere," EURASIP Journal on Advances in Signal Processing, 2012, 1-11(2012).
- [13] Olsen, E.T. (ed.), "AIRS/AMSU/HSB Version-6 level 2 quality control and error estimation, version 1.0, Jet Propulsion Laboratory, Pasadena, CA. Retrieved from http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v6_docs (2012).
- [14] Susskind, J., Molnar, G., Iredell, L., and Rosenberg, R., "Recent advances in improvement of forecast skill and understanding climate processes using AIRS Version-5 product," Proc. of SPIE 8511, Infrared Remote Sensing and Instrumentation XX 85110Q, DOI:10.1117/12.930998 (2012).